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MILITARY HYDROLOGY

Report 2

FORMULATION OF A LONG-RANGE CONCEPT FOR STREAMFLOW PREDICTION CAPABILITY

by

Wesley P. James

Texas A&M University
Civil Engineering Department
College Station, Tex. 77843

July 1980

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The army that has the capability of predicting streamflows throughout the battlefield area some several hours in advance should have a tactical advantage on both offense and defense. Continuous simulation of all the streams in the area would be desirable. Time, data, and manpower constraints may limit the hydrologic procedures utilized by the military hydrologist and continuous simulation of the streamflow may not be possible. This report reviews alternate procedures for predicting streamflows and presents a long-range concept for

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streamflow prediction capability. The following conclusions were developed during this study:

a. Alternate streamflow forecasting procedures should be developed to meet the long-range hydrologic needs of the military.

b. The hydrologic cycle is very complex and shortcut methods of forecasting streamflows can result in considerable error if the limitations of the procedure are exceeded.

c. Peak flow flood formulas will have limited application to military hydrology.

d. A long-term effort should be devoted towards the development of a world-wide hydrologic data base.

e. An effort should be devoted to relating stream discharge and stage frequency to basin and channel parameters for various regions of the world.

f. Long-term development of hydrologic technology should not be restricted to present computer capabilities but should be based on a reasonable estimate of future capabilities of computer facilities available to the military hydrologist.

g. Long-term development of hydrologic technology should be compatible with other long-range plans of the Army.

h. New hydrologic technology should be designed to fully utilize the future remote sensing capability of the military.

i. Event simulation models can provide streamflow prediction capability for watersheds having insufficient data for continuous simulation models.

j. Long-term efforts should be directed towards developing a continuous streamflow simulation model compatible with military constraints and requirements.

k. The military hydrologist must be trained to utilize the advanced technology.

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PREFACE

Work for this report was conducted for the U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi, under Contract No. DACA39-79-M-0143, Department of the Army Project No. 4A762719AT40, "Mobility and Weapons Effects Technology," Task Area BG, "Military Hydrology," Work Unit 029, "Military Hydrology Technology Advancement." The study was sponsored by the Assistant Chief of Engineers, Office, Chief of Engineers (OCE). Messrs. Herman Roeland and Walter Swain were Technical Monitors for OCE during the conduct of the study and preparation of this report.

The study was conducted at Texas A&M University by Dr. Wesley P. James during the period of 1 August 1979 through 31 December 1979. The report was prepared by Dr. James and typed by Lori Baldwin.

The contract was monitored technically by Dr. L. E. [illegible], Environmental Constraints Group (ECG), Environmental Syst[illegible] (ESD), Environmental Laboratory (EL), WES, and Mr. J. G. [illegible], under the general supervision of Mr. B. O. Benn, Chief, ESD, and Dr. J. Harrison, Chief, EL.

COL J. L. Cannon, CE, and COL N. P. Conover, CE, were Directors of WES at the time the study was conducted and during preparation of this report. Mr. F. R. Brown was Technical Director.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
acres	4046.856	square metres
cubic feet per second	0.02831685	cubic metres per second
feet	0.3048	metres
inches	25.4	millimetres
square miles	2.589988	square kilometres

MILITARY HYDROLOGY

FORMULATION OF A LONG-RANGE CONCEPT FOR STREAMFLOW PREDICTION CAPABILITY

PART I: INTRODUCTION

1. Many of the techniques presently being used for estimating streamflows were developed for the design of engineering projects. These flows are generally major events with a specific probability of occurrence during the life of the project. The military hydrologist may also be required to determine the magnitude of floods with specified return periods, but most of his work will be in the forecasting mode. He will be required to estimate the discharge, velocity, depth, and width of the flow at sites along streams from measured or predicted precipitation patterns and will be concerned with a full range of events from minor to major floods. Watershed characteristics such as vegetation, soil moisture, and soils have a greater influence on streamflows for minor floods than for major events; hydrologic procedures used in the design of engineering projects might not be adequate for military hydrology.

2. Hydrologic procedures selected for military application should:

a. Require a minimum of historical information.

b. Have parameters that are related to physical characteristics of the watershed and that can be evaluated remotely.

c. Be simple and reliable and require minimum effort and time to adopt to an area.

d. Not be dependent on the judgment of the user.

e. Consistently provide accurate results.

3. Hydrologic procedures in this report are discussed under the topics of General Guidelines, Peak Flow Formulas, and Streamflow Simulation Models.

PART II: HYDROLOGIC PROCEDURES

General Guidelines

4. The military hydrologist may be required to develop a best estimate of streamflows for an area with limited data, manpower, and/or time. Some general guidelines for various areas of the world could be developed to serve the hydrologist for both planning and executing operations. Guidelines would have to be developed for each area or physiographic province having distinctive climate, geology, landforms, topography, soils, and precipitation patterns.

Channel geometry

5. Information on the history of the stream can be obtained from the characteristics of the channel and adjacent floodplain. Natural channels adjust their geometry to a range of flows as they attempt to maintain a dynamic stability in response to varying input conditions. Hey (1978), in a study of hydraulic geometry of river channels, defined dominant discharge as the constant flow that develops the same gross channel shapes and dimensions as the natural sequence of dicharges. According to this study, bank-full flow is responsible for transporting the largest volume of sediments and should be considered the dominant discharge. The frequency of bank-full flow for stable channels was related to the characteristics of the river. For stable gravel bed rivers in the United Kingdom, the return period of bank-full flow was 1.5 years based on the annual series, while for sand bed channels, bank-full flow occurred more frequently. For unstable channels the frequency of bank-full flow was modified, occurring less frequently in eroding channels and more frequently in depositing ones.

Channel width

6. Riggs (1978) developed a method of estimating flood characteristics from the whole-channel width. In perennial streams, the whole-channel width is the width of flow at bank-full stage or the distance between the inside edges of the floodplain as defined by the break in slope. For an ephemeral stream, a floodplain may not exist and the

reference level should reflect the present flow regime. Estimation of flow characteristics from channel size is considered an operational technique by the Water Resources Division of the U. S. Geological Survey (USGS) (Riggs 1978).

7. The relation of whole-channel width and 10-year flood flow for streams in western North America is shown in Figure 1. The differences in the flow-width relationship appear to be related to channel type and flood regime rather than geographic location. Riggs reported that the use of channel size to estimate streamflow is not applicable to reaches of streams that have meandering channels bordered by heavy brush, braided channels, and ephemeral drainages which flow so infrequently that a defined channel is not developed. The two major problems with using channel size as a flow indicator are recognizing the present state of the channel and selecting a representative width. Most streams change type throughout their lengths and it is usually possible to find a suitable reach and section for measurement somewhere near the point of interest. Criteria for reach selection are: (a) channel shape uniform throughout, (b) bed and banks composed of material that has permitted the channel to develop into a normal size for the flow regimen, and (c) channel banks appear to have been permanent for some years.

Classification of stream channels

8. Schumm (1963) developed a tentative classification of alluvial river channels. Observations for this study were of rivers in the western United States with channels containing less than 20 percent coarse gravel and with well-developed floodplains. As shown in Table 1, nine subclasses of channels were identified on the basis of predominant mode of sediment transport, combined percentage of silt-clay fractions in channel sediments, proportions of suspended and bedload sediments, and channel stability characteristics. Also shown are channel gradient characteristics and/or the impacts of erosion and deposition on channel shape.

Channel equations

9. Leopold and Maddock (1953) demonstrated a correlation of stream depth d, surface width w, and velocity V with stream

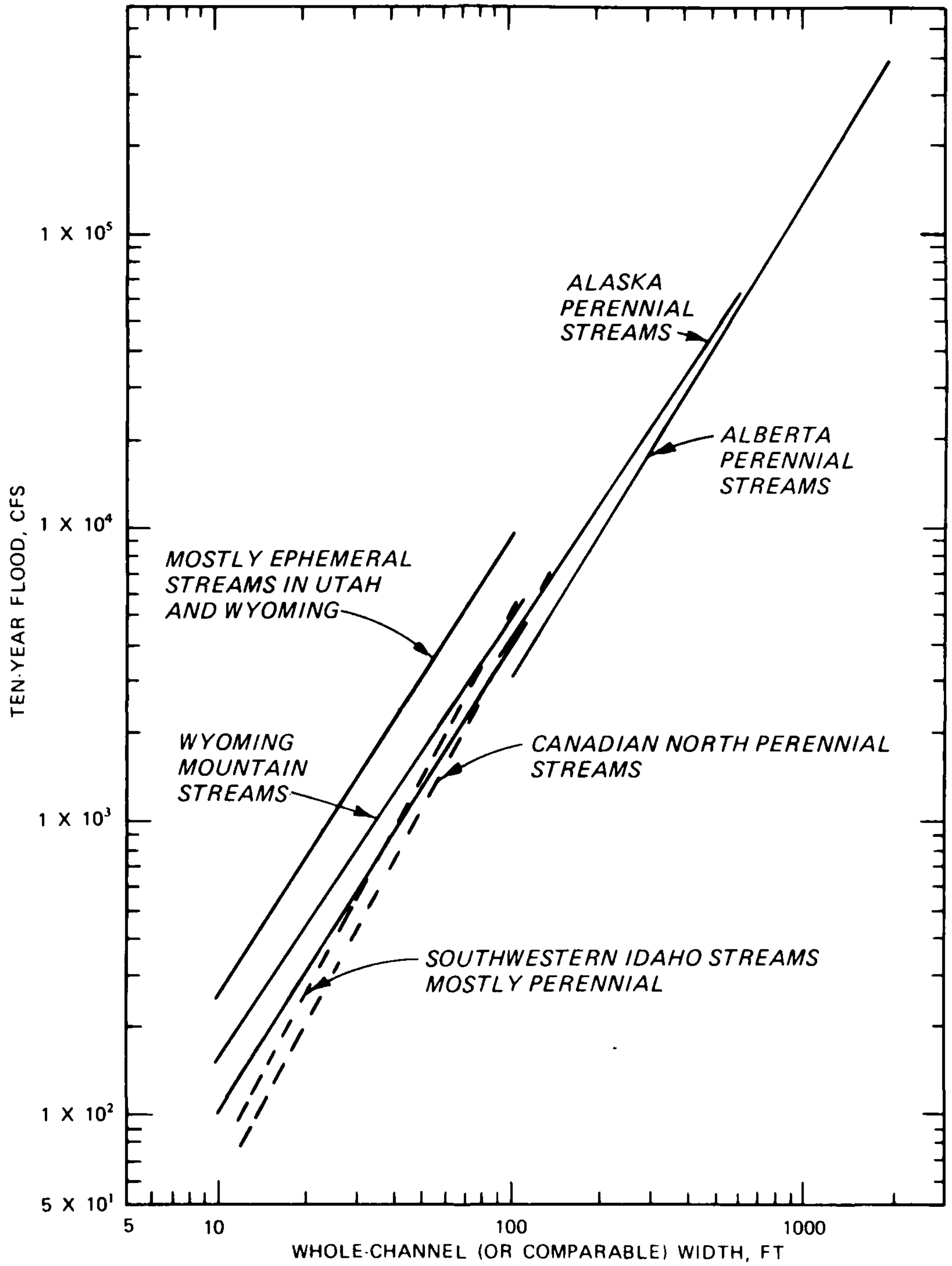

Figure 1. Channel width vs. 10-year flood flow for streams in western North America

discharge Q . The relations can be written as:

$$V = kQ^m , \quad w = aQ^b , \quad d = cQ^f$$

where k , a , and c are coefficients and the exponents m , b , and f must satisfy

$$m + b + f = 1$$

In a study of river cross sections in semiarid parts of the United States, the exponents had average values of

$$m = 0.1 , \quad b = 0.5 , \quad f = 0.4$$

Bank-full floods

10. In terms of the annual maximum series, the range of return periods quoted in the literature is 1.07 to 3.0 years for bank-full floods. Woodyer (1968) in a study of streams in New South Wales obtained a range of 1.02 to 1.21 years for the middle bench (terrace) and 1.23 to 2.69 for the high bench based on the annual maximum series. Because of recent incision of floodplains, the middle bench was considered equivalent to bank-full flow, while the upper bench was considered equivalent to the floodplain flow.

Floodplain floods

11. For streams which have not been improved hydraulically nor controlled by reservoirs, a specific return period flood will generally inundate the floodplain as delineated on aerial photography. From a review of several Soil Conservation Service (SCS) soil survey reports of the Texas area, fluvial soils are generally inundated on an average of 5 to 10 years.

12. The Bureau of Public Roads (Potter, Stovicek, and Woo 1968) conducted a study of 99 streams with watershed areas of less than

400 square miles* and located in the United States east of the Mississippi River. The purpose of the study was to develop a relation between the stream cross section and the 10-year recurrence interval flood. For each stream the cross-sectional areas were computed and plotted (log scale) against the corresponding depth (linear scale) on semilogarithmic paper. Each plot in the study showed the consistent feature of becoming a straight line after passing a certain depth. The corresponding discharge for this depth was determined to have a 10-year recurrence interval for a stable, unregulated stream (see Figure 2).

<u>Rating curves</u>

13. Using the Manning equation, the discharge of a stream may be computed from the slope of the water surface, the cross-sectional area, and the channel roughness. Riggs (1976) developed a simplified slope-area method for estimating flood discharges in natural channels. He found that the channel roughness coefficient was related to the water surface slope and Manning's equation could be reduced to

$$Q = aA^{b}S^{c} \tag{1}$$

where

Q = streamflow rate, cu m/sec

A = cross-sectional area, sq m

S = water surface slope, m/m

a,b,c = constants to be evaluted from historical data

If historical information is not available, Manning's equation could be utilized to estimate flow rate. The terms in the equation can be evaluated from maps and aerial photography.

<u>Flood frequency</u>

14. Flood frequency distribution is used to determine the discharge rates for various return period floods. The Gumbel and log Pearson Type III distributions are commonly used to relate flood magnitude and

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* A table of factors for converting U. S. customary units of measurement to metric (SI) is presented on page 3.

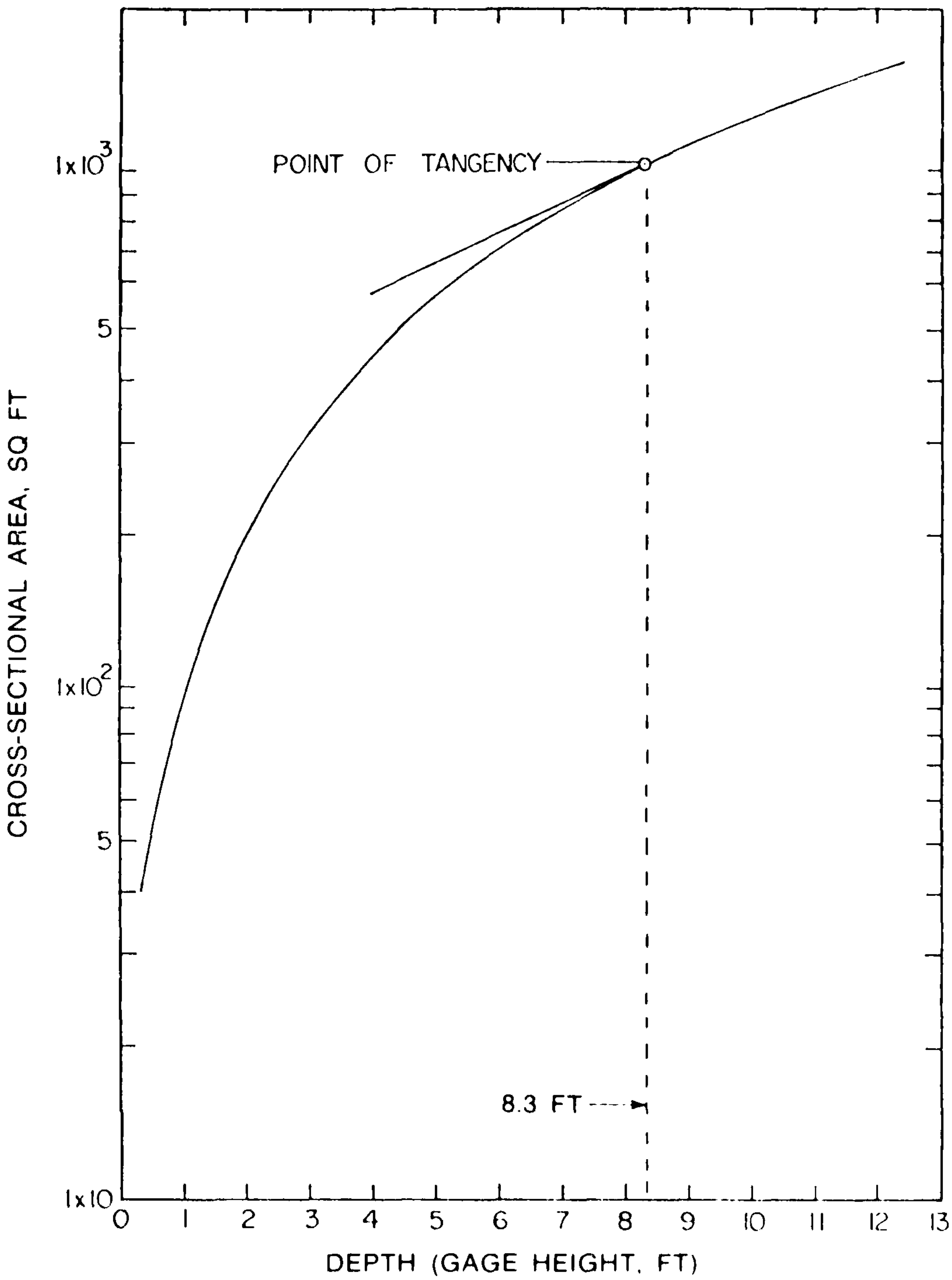

Figure 2. Typical depth-area curve

probability. If a flood-frequency distribution is assumed and two points (2-year; bank-full flow and 10-year floodplain flow) are known, the flood flow for any other return period can be estimated. However, Potter (1958) observed that when the maximum annual peak rates of run-off were plotted on Gumbel probability paper, the frequency curve could best be represented by two straight lines (see Figure 3). The lower line represents the distribution of flows with return periods of 5 years or less, while the upper line represents the distribution of flows with return periods of 10 years or greater; the line best representing flows with return periods between 5 and 10 years varies from stream to stream. Where minor floods are of special interest, the partial duration series should be used instead of the annual series. This will tend to make a larger dogleg in the distribution plot.

Precipitation

15. It is generally assumed that the flood flows and the precipitation producing these flows have the same return period; that is, a 10-year rainfall will produce a 10-year flood. Thus a detailed rainfall frequency atlas of the world (similar to the Weather Bureau TP-40 for the United States) could be developed and utilized by the military hydrologist. For example if a 3-in., 6-hr rainfall is forecast for an area, the hydrologist utilizing the rainfall frequency atlas could determine the return period for this storm. For this example, assume that the return period of the storm is 1 year. If the bank-full flow return period is 2 years for the area, it could immediately be estimated that the streams will be flowing at less than bank capacity. However, if it is a 5-year return period rainfall, then some over-bank flooding can be expected.

Peak Flow Formulas

16. Formulas for estimating runoff from watersheds are discussed under the classification of either empirical or statistical. Empirical formulas are the easiest to develop and apply but often give very inaccurate results. Statistical formulas are developed from historical

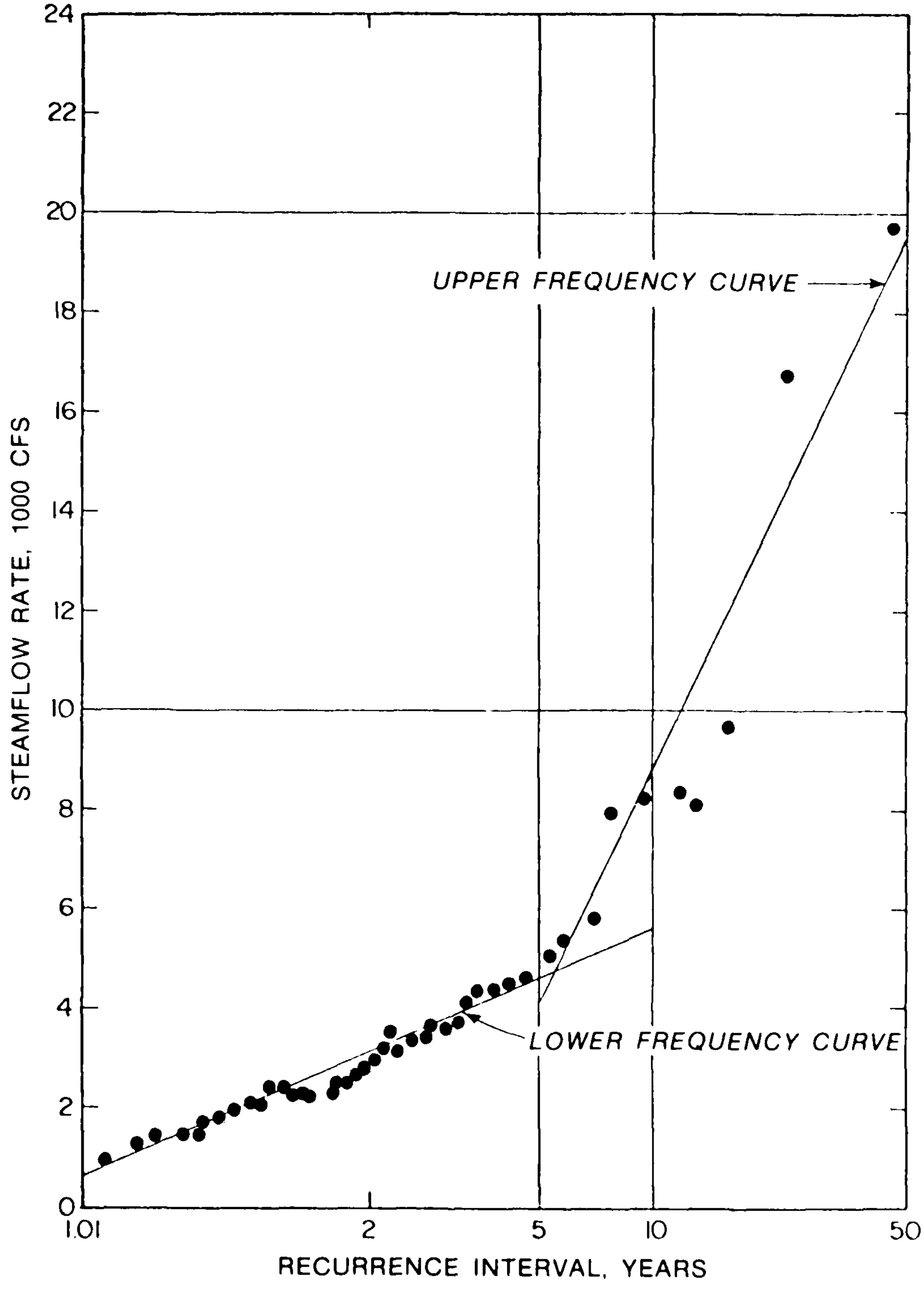

Figure 3. Upper and lower frequency curves

data of the region and usually relate several physical characteristics of the watershed to probable streamflow rates. Empirical formulas are generally used to relate precipitation to streamflow while statistical formulas usually are not.

Empirical procedures

17. Talbot formula. If flood records for an area are available and a log plot is made of the peak flow per unit of drainage area Q_p vs. drainage area A_d, the enveloping curve defining the upper limit is

$$Q_p = CA_d^n \tag{2}$$

where C and n are empirical factors. This equation is commonly referred to as the Talbot formula. Since there is no return period associated with the peak flow, this type of analysis has limited value.

18. Rational method. The rational method is often used to estimate peak runoff flows from small watersheds. It has been in general use in the United States and England since about 1850 and is often used today for the design of stormwater systems in urban areas and highway cross drainage structures for small watersheds. The basis for this method is the formula

$$Q_p = CIA \tag{3}$$

where

Q_p = peak flow, cfs

C = a dimensionless runoff coefficient

I = rainfall intensity, in./hr

A = drainange area of the watershed, acres

19. While the strength of this method is its simplicity, it has very definite limitations in design or forecasting applications. For the rational method to be applicable, the rainfall must be of uniform intensity and have a duration equal to or greater than the time of concentration for the basin.

20. Since the time of concentration will generally increase with

the basin size and the chance of a storm occurring with a uniform intensity decreases with the storm duration, this procedure is only applicable to small watersheds. The accuracy of the rational method decreases as the size of the drainage area increases. For estimating flows, the method should be used with caution for areas greater than 100 acreas and probably should not be used for areas in excess of 1200 acres. The method should be used with caution to forecast the peak flow from an actual rainfall since the rainfall intensity may not be reasonably constant or the duration may not be equal to or greater than the time of concentration. In addition, the method does not provide any information on the time distribution of the runoff.

21. The time of concentration is considered to be the longest combination of overland flow and channel flow time that exists in the basin. Time of concentration must be known when using the rational method to determine whether a given duration stress can be analyzed. The channel flow time can be estimated as the channel length divided by the estimated average channel velocity. Overland flow velocity can be estimated from tables or graphs relating velocity to slope and surface conditions, empirical equations developed from experimental tests, or equations for laminar overland flow. Since the surface is seldom flat, the runoff soon flows into slight channels or rills. Sheet flow generally does not extend for large distances and travel time estimated by theoretical equations for overland flow may be difficult to accurately apply.

22. To span a broad set of conditions ranging from heavily forested watersheds with steep channels and high runoff coefficients to smooth meadows and paved parking lots, the SCS developed a curve number method of estimating basin lag for watersheds up to 2000 acres. The method relates flow length, slope, and curve number to basin lag. The approximate relationship used between basin lag T_ℓ in hours and time of concentration T_c in hours is:

$$T_c = 1.6\ (T_\ell) \tag{4}$$

23. The runoff coefficient C indicates the amount of runoff as a

decimal fraction of the rainfall. It will typically range from 0.10 to 0.90 for rural areas and is a function of slope, land use/cover, and soil type. The coefficient is not constant for a watershed. Higher values are required for large storms or for high soil moisture conditions in the watershed prior to the storm.

24. McMath and Burkli-Ziegler formulas. In order to incorporate the effects of slope S of the drainage basin (in feet per 1000 ft) into the rational method, an empirical formulation is used:

$$Q = CIA \left(\frac{S}{A}\right)^x \tag{5}$$

where x has a value of 0.25 for the Burkli-Ziegler runoff formula and 0.5 for the McMath runoff formula.

25. Gage relations. Gage relations are particularly useful for flood forecasting of major streams where local inflow is small compared to the mainstream flow. It is simple empirical solution to flood wave routing. Graphs correlating observed stage or discharge at one or more upstream stations with the resulting stage or discharge at a downstream station are developed. More complex gage relations can be constructed to account for variable local inflow.

Statistical formulas

26. Equations based on standard flood frequency distributions are generally in the form

$$Q_p = Q_{ave} + K\sigma \tag{6}$$

where

Q_p = estimated peak discharge for flood associated with recurrence interval of interest

Q_{ave} = average peak discharge for floods of record

K = frequency factor (function of recurrence interval and skewness)

σ = standard deviation of peak discharges for floods of record

27. Strahler (1957) conducted a quantitative analysis of watershed geomorphology using two general classes of descriptive numbers

scale measurements, and (b) dimensionless numbers. Linear scale measurements include length of stream channels of a given order, drainage density, basin perimeter, and relief. If two drainage basins are geometrically similar, all corresponding length dimensions will be a fixed ratio. Dinensionless properties include stream order numbers, stream length and bifurcation ratios, junction angles, maximum valley side slope, mean slope of watershed surfaces, channel gradients, relief ratios and hypsometric curve properties. He reported that dimensionless properties can be correlated with hydrologic and sediment-yield data.

28. Carlston (1963) in a study of drainage density and streamflow found that flood runoff as measured by the mean annual flood $Q_{2.33}$ per square mile varies with the drainage density D in the form

$$Q_{2.33} = 1.3D^2 \tag{7}$$

The relation of mean annual flood to drainage density in 15 basins in the eastern United States was not affected by large differences among the basins in relief, valley-side slope, stream slope, or precipitation patterns. In a study conducted for the Highway Research Board by Brock et al. (1972), several sets of regression equations relating peak flows to topographic parameters, hydrologic and climatic factors, and soil parameters were developed. The research was based on 493 watersheds with an area of 25 square miles or less and more than 12 years of streamflow records. Topographic characteristics of the basins had the greatest influence on peak flow. Among the topographic variables, the length of tributaries, area, and stream slope were the most important.

29. A set of regression equations were developed for four regions of the United States for various return periods by Thomas and Benson (1970). The equations relate basin characteristics to peak discharge. The data base for the regression analysis consisted of 45 watersheds in each of four regions. Input data requirements included area of watershed, slope of main channel, length of main channel, surface storage area, soil infiltration index, 2-year 24-hr rainfall, mean annual snowfall, and forest cover factor. Results of this regression

analysis indicated that streamflow characteristics can be defined more accurately in humid eastern and southern regions than in the more arid western and central regions and that medium flows can be more accurately defined than high flows.

Streamflow Simulation Models

30. Simulations of a surface water system can be used to match historical events and forecast streamflows. Physical, analog, hybrid, and digital models have been employed for simulating the behavior of hydrologic systems. In recent years, digital computer simulation has become a practical engineering procedure. While there are many ways to classify simulation models, for the purpose of this report, they will be discussed in terms of short-term simulation models and continuous simulation models. The short-term hydrologic models are generally used to simulate the streamflow for a single storm event while the continuous simulation models are generally used to develop the streamflow for an extended period of time.

Short-term hydrologic models

31. The basic calculations utilized by most short-term hydrologic models can be grouped into three steps: (1) rainfall to runoff conversion, (2) time distribution of runoff, and (3) translation of hydrograph downstream or routing. The application of most event simulation models requires that the watershed be divided into homogeneous subbasins. Different rainfall values and parameters can be utilized for each subbasin. Computations begin at the upstream subbasin and proceed downstream. From the rainfall-runoff relations and the time distribution of runoff, storm hydrographs are computed for each subbasin. The storm hydrographs are routed and added as required to develop the main channel flood hydrograph.

32. As discussed by Pabst and Cermak (1977), there are alternate methods of performing each of the three steps listed above. The rainfall to runoff conversion could be estimated by the SCS curve number procedure, the antecedent precipitation index, loss rate functions, or

soil moisture accounting. Unit hydrographs and simple time-lag isochromes are, in general, used by hydrologists for determining the time distribution of runoff; however, overland flow routing is coming into more widespread use. Most short-term hydrologic models use simple hydrologic routing procedures for translating the hydrographs downstream rather than the more complex hydraulic routing procedures.

33. Based on presently available technology and the specific hydrologic problem, the most compatible method of converting rainfall to runoff, determining the time distribution of runoff, and routing of hydrographs can be determined. In general, the complex procedures require detailed input data to yield accurate results. Hydrologic procedures for general military applications are qualitatively evaluated in Table 2. This evaluation is based on the criteria established earlier in the report. Special hydrologic problems or conditions such as the dam-break flood and mobility are not considered in this evaluation. The SCS curve number procedure, unit hydrograph, and hydrologic routing are discussed in more detail in the following sections.

34. SCS curve number method. The SCS curve number (CN) method of estimating direct runoff from rainfall is based on about 30 years of experience and was developed specifically for ungaged watersheds. It is often used and gives reasonable results under a wide range of soil, topographic, and climatic conditions. The method does not consider rainfall intensity and duration. It is based on the assumption that:

$$\frac{I}{A_p} = \frac{R}{R_p} \tag{8}$$

where

I = infiltration

A_p = potential abstraction

R = runoff

R_p = potential maximum runoff

With I equal to $R_p - R$, then:

$$R = \frac{\left(R_p\right)^2}{R_p + A_p} \qquad (9)$$

35. The initial abstraction consists mainly of interception, surface storage, and the infiltration before runoff begins. From studies on experimental small watersheds, it was found that the initial abstraction was equal to approximately 20 percent of the potential maximum abstraction. Therefore, the potential runoff R_p is related to the precipitation P and initial abstraction A_I by:

$$R_p = P - A_I = P - 0.2\ A_p \qquad (10)$$

and

$$R = \frac{\left(P - 0.2\ A_p\right)^2}{P + 0.8\ A_p} \qquad (11)$$

The potential abstraction A_p is related to soil, soil cover, land use, and antecedent moisture conditions. The runoff curve number (CN) is defined as:

$$CN = \frac{1000}{A_p + 10} \qquad (12)$$

or

$$A_p = \frac{1000}{CN} - 10 \qquad (13)$$

For a condition where the potential abstraction is zero, the curve number is 100 and the amount of runoff would equal the amount of precipitation. Curve numbers for various soil-moisture complexes have been evaluated and a brief summary is presented in Table 3.

36. In reference to Table 3, the four main factors influencing the curve number are land use, treatment, hydrologic condition, and hydrologic soil group. Land use indicates the watershed cover and includes type of vegetation, litter and mulch, and fallow as well as non-agricultural uses. Land treatment applies mainly to agricultural land use and it includes mechanical practices such as contouring or terracing and management practices such as grazing control or rotation of crops. Land use and treatment classes include cultivated land, grassland, woods and forest, and urban lands. Land use and treatment classes can be estimated reasonably accurately from aerial photography and to a limited extent from satellite imagery.

37. Hydrologic condition reflects the runoff producing potential of the area generally with regard to the vegetation density. For pasture lands, the hydrologic condition is influenced by the amount of grazing and can be quantitatively evaluated by tons per acre of plant and litter or the percent bare ground. Type of forest, depth and type of humus, and understory should be considered when estimating the hydrologic condition of woods and forests.

38. The hydrologic soil groups, as defined by the SCS, are:

a. Soils having low runoff potential. Soils having high infiltration rates even when thoroughly wetted and consisting chiefly of deep, well-drained to excessively drained sands or gravels. These soils have a high rate of water transmission.

b. Soils having moderate infiltration rates when thoroughly wetted and consisting chiefly of moderately deep to deep, moderately well to well-drained soils with moderately fine to moderately course textures. These soils have a moderate rate of water transmission.

c. Soils having slow infiltration rates when thoroughly wetted and consisting chiefly of soils with a layer that impedes downward movement of water, or soils with moderately fine to fine textures. These soils have a slow rate of water transmission.

d. Soils having high runoff potential. Soils having very slow infiltration rates when thoroughly wetted and consisting chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a claypan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very slow rate of water transmission.

39. The curve numbers tabulated in the table are for average soil moisture conditions. When there are several storms a few days apart, the initial abstraction of the watershed is reduced with each succeeding storm and the curve number should increase. For the SCS method, the change in curve number is based on an antecedent moisture condition (AMC) determined by the total rainfall in the 5-day period prior to the storm. Three levels of AMC are used: AMC-I is the lower limit of moisture, AMC-II is the average soil moisture conditions, and AMC-III is the upper limit of soil moisture conditions in the watershed. Table 4 shows corresponding CN values associated with AMC's I, II, and III.

40. Hawkins (1978) developed a procedure for adjusting the curve number which utilized evapotranspiration losses ET, interim rainfall inputs P, and runoff R. The relation between the curve number at time two CN_2 and the curve number at time one CN_1 is

$$CN_2 = \frac{1200}{\frac{12}{CN_1} + [ET - (P - R)]} \tag{14}$$

Moisture losses to evapotranspiration and drainage should be limited by site conditions. Curve numbers listed for AMC-I and AMC-III in Table 4 might be considered limits but this would deny the possibility of the curve number approaching 100 (saturation). The effects of infiltration capacity and site moisture properties on curve number need to be explored and incorporated into the procedure.

41. Unit-hydrograph method. The rationale for the unit-hydrograph method is that identical rainstorms over a basin with identical conditions prior to the rain will produce identical runoff hydrographs. A unit hydrograph is a hydrograph with 1 in. of runoff resulting from a rainstorm of specified duration and areal pattern. To limit the number of unit hydrographs for a basin, a uniform rainfall over the basin is assumed. This assumption is reasonable for small basins but variations

over large areas are usually too great to be ignored. The size of watershed for which the method can be utilized is limited by the type and size of storm. It is generally not advisable to utilize the method for watersheds greater than 2000 square miles. This upper limit may be adequate for general frontal type rains, but, for local convective rains, the limit should probably be considerably smaller.

42. The basis of the unit-hydrograph approach is the assumption of linearity; that is, the direct runoff hydrograph ordinates of a storm with 2 in. of runoff are two times the unit hydrograph ordinates of the same duration. This assumption may not be completely valid as the unit hydrograph peaks tend to be higher and occur earlier as the volume of runoff increases. It is assumed that the shape of the unit hydrograph defines the runoff characteristics of the basin.

43. Large variations in rainfall intensity may occur during a storm. This will adversely affect the accuracy of the unit-hydrograph method. To minimize errors from this source, short-duration unit hydrographs are used to develop hydrographs resulting from longer rains. If the storm is divided into two or more parts each with uniform intensity, the hydrographs of each part are computed separately and added. Experience has shown that the best time period to use is about one fourth the basin lag.

44. The unit-hydrograph method is applicable to military hydrology. In many cases, streamflow records for the watershed will not be available and synthetic methods of developing the unit hydrograph will be required. The Clark, the Snyder, the two-parameter gamma response, and the SCS unit hydrograph methods are generally applicable for developing the unit hydrograph from watershed characteristics.

45. Routing. Streamflow simulation models generally employ some form of routing procedures. Routing is used to estimate the temporal and spatial variations in the flood wave as it traverses a reach of stream or reservoir. Routing techniques are classified into either hydrologic or hydraulic. Hydrologic routing uses the continuity equation with a relationship between storage and discharge for the stream or reservoir. Those hydrologic routing procedures that do not require

historic inflow and outflow hydrographs to develop the relationship between discharge and storage are the most applicable to military hydrology. Hydraulic routing is used to describe unsteady flow and utilizes both the equation of continuity and the equation of motion in the form of partial differential equations. Detailed information on the channel characteristics and the use of a high speed digital computer are required.

46. Graphic and tabular methods. Graphic and tabular methods of estimating peak discharges for a given rainfall event are presented by the U. S. Soil Conservation Service (1975). These methods are approximations of the unit-hydrograph event simulation model and are based on a 24-hr duration, AMC-II rainfall distribution. They utilize the SCS curve number procedure previously discussed. The tabular method can be used to develop composite hydrographs at any point within a watershed by dividing the watershed into subareas and computing the time of concentration for each subarea and the travel time through each reach. The graphic method uses only the time of concentration and is applicable to a watershed where runoff characteristics are uniform and valley routing is not required.

Continuous simulation models

47. Ideally, the battlefield commander should at all times have information on stages and flow rates for all the streams in the battlefield area. This would require the use of a continuous simulation model. There are a number of continuous simulation models available, and some of these are summarized in Table 5. Most of these models have a large number of parameters to be evaluated. Model calibration involves manipulating the parameters to reproduce an historical record within some range of accuracy. This can be accomplished by trial and error or automatic optimization. However, the models require a considerable amount of historical data that would not be available for an ungaged watershed. One model listed has fixed parameters where the values are established by measurement of physical characteristics of watershed.

48. Manley (1975) reports on the development of a hydrologic model with physically realistic parameters. He indicated that one

advantage of this model is that it offers potential for application to ungaged watersheds by using parameter values that have been obtained for similar gaged watersheds or from physical measurements. To fit the model to a catchment, it is necessary to obtain values for the parameters, most of which can be assigned from a knowledge of soil types, measurements of the catchment, and analysis of past flows. The model was applied to two basins (414 km^2 clay area and 83 km^2 limestone area). In both cases, 1 year of record was used for fitting the model, and an independent 2-year period was used for testing the accuracy. The correlation coefficients for the mean daily flows were 0.96 and 0.93.

49. Dawdy and Bergmann (1969) concluded that the spatial variability of rainfall is a critical factor affecting simulated streamflows. This is an example of nonavailability and inadequacy of hydrologic inputs. For this reason and possible overreliance on outputs, sophisticated models may have limited utility in application.

PART III: CONCLUSIONS

50. The hydrologic cycle is very complex and shortcut methods of forecasting streamflows can result in considerable error if the limitations of the procedure are exceeded. Primarily, errors result from the use of procedures that are not amenable to various precipitation patterns and distributions as well as the variation in the response of the catchment to precipitation. Graphic procedures can be developed to aid the hydrologist, but limitations and estimated accuracy should be clearly stated.

51. Peak flow flood formulas will have limited application to military hydrology. Peak flow formulas have been developed primarily for planning and design purposes and not for forecasting the streamflow resulting from a storm of specific spatial and temporal patterns. The empirical formulas relating rainfall to runoff are only applicable to very small drainage areas, and serious error can occur when they are applied to larger drainage areas. Statistical peak flow flood formulas are developed for a region and can give reasonable values of specific return period floods for that region. They are not used to directly forecast streamflows.

52. Event simulation models can provide a streamflow prediction capability for watersheds having insufficient data for continuous simulation models. Event simulation models are, in general, used by the engineering community and can be adopted for military application. For this purpose, the SCS curve number procedure for estimating runoff, the synthetic unit-hydrograph method for estimating the time distribution of runoff, and the hydrologic discharge/storage routing procedure for translating hydrographs downstream appear to be the most suitable computational procedures for the model. Most of the process parameters for this type of model can be related to physical characteristics of the watershed or stream and can be evaluated remotely.

53. The military hydrologist must be trained to utilize the advanced technology. Long-range concepts for stream flow prediction are based on the assumption that trained personnel will be available to

perform the hydrologic analyses. The use of advanced technology in conducting hydrologic studies will not reduce the need for trained personnel but will require a higher order of professional competence. Without adequate training, the military hydrologist will not be able to make the best decisions, judge the adequacy of the input data, or estimate the accuracy of the results.

PART IV: RECOMMENDATIONS

54. Long-range concepts for streamflow prediction capability should incorporate advanced computer technology and make full utilization of remote sensing. Both remote sensing technology and minicomputer technology have advanced considerably in the last several years. Improvement in these technologies can be expected to continue in the future.

55. New hydrologic technology should be designed to fully utilize the future remote sensing capability of the military. Remote sensing techniques can be utilized to collect much of the data required for streamflow forecasting. Watershed characteristics such as land cover, land use, soils, and topography can be evaluated from aircraft and satellite imagery. Laser profiles and aerial photography can provide information on the channel cross section. Much of the technology has been developed in the last few years and future advances can be anticipated.

56. Long-term development of hydrologic technology should not be restricted to present computer capabilities but should be based on a reasonable estimate of future capabilities of computer facilities available to the military hydrologist. Over the last several years, there have been tremendous advances in minicomputers. Today, for example the HP 9800 system 45 desktop computer is available for $20,000 and has 62 k byte user memory, CRT with graphics package, two 217 k byte tape cartridge drives, and a built-in thermal line printer. The size of the minicomputer will continue to decrease while the capability, portability, and reliability will continue to improve. It should not be long before a backpack minicomputer is available for field use.

57. Long-term development of hydrologic technology should be compatible with other long-range plans of the Army. Terrain analysis for cross-country mobility requires much of the same data as that required for streamflow predictions. To the extent possible, common data bases and data management procedures should be developed for cross-country mobility and hydrology. If digital terrain information on

soils, topography, and ground cover is expected to be available, then the more advanced hydrologic procedures should be developed to utilize these data. For most areas, the resolution of the digital terrain data should be adequate for overland flow routing but probably not adequate for channel routing. Channel routing will require more detailed information on channel geometry.

58. A military unit will be responsible for conducting a hydrologic assessment of an area. It is assumed that trained personnel will be available for the hydrologic analysis and that historic data bases will exist. The four general steps in making this assessment are briefly outlined below and shown in Figure 4.

a. Statement of Problem. Define both the long- and short-term military hydrologic requirements for the area and identify constraints.

(1) Streamflow forecast requirements

a. Location

b. Variables

c. Duration

d. Accuracy

(2) Constraints

a. Time

b. Personnel

c. Facilities

d. Data

b. Methods and Procedures. Select methods of analysis and determine input data requirements compatible with the project requirements and constraints.

(1) Methods of analysis

a. General guidelines

b. Event simulation

c. Continuous simulation

(2) Input data requirements

a. Physical data

1. Watershed

2. Channel

b. Hydrometeorological

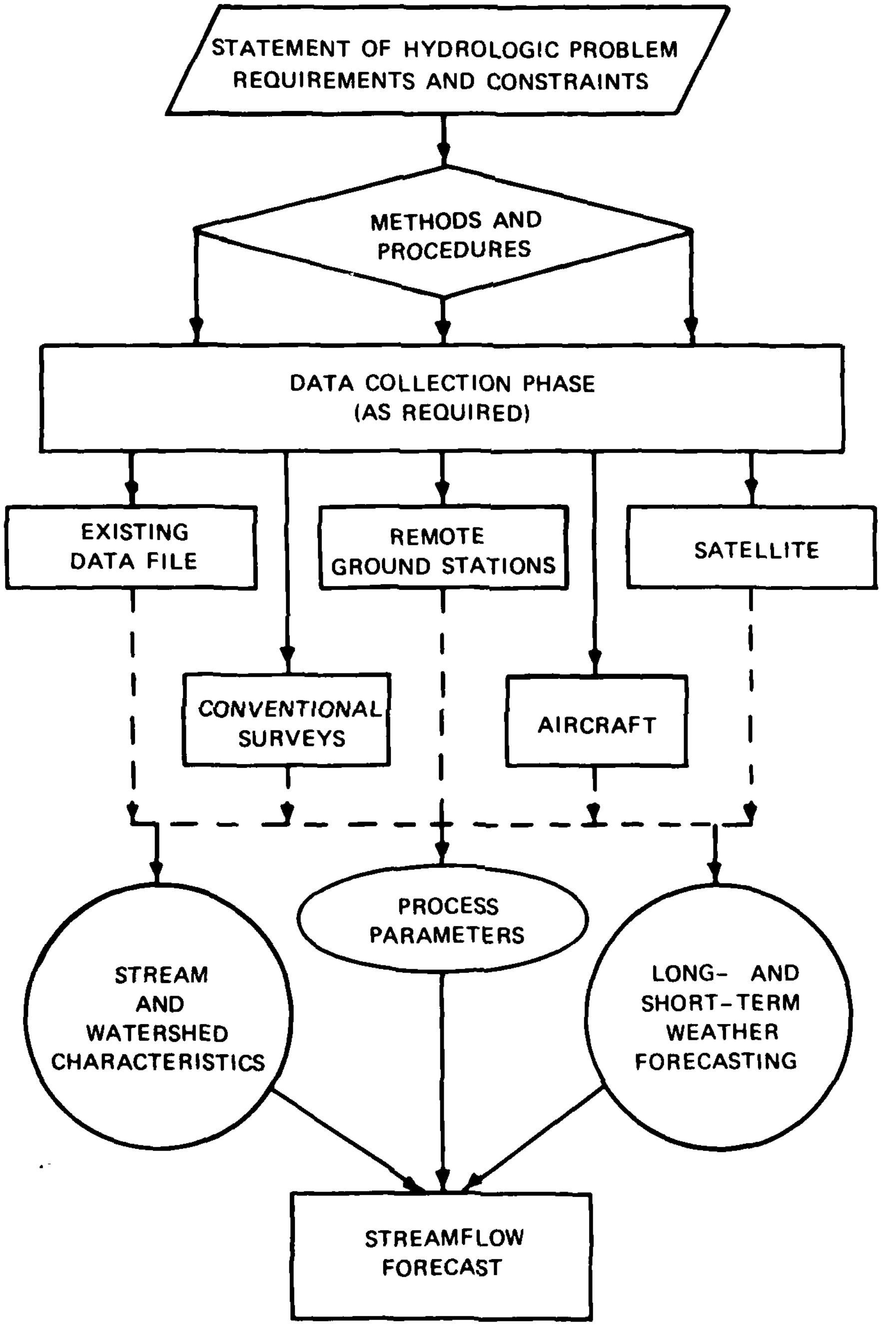

Figure 4. A general hydrologic assessment flowchart for terrain team

1. Weather

2. Streamflow

c. Process parameters

c. Data Collection. Formulate plans to acquire necessary data.

(1) Existing data files

(2) Conventional surveys

(3) Remote ground stations

a. Automatic/telemetric

b. Radar

(4) Aircraft

a. Aerial photography

b. Thermal imagery

c. Microwave imagery

d. Laser profiler

(5) Satellite imagery

d. Hydrologic Analysis. Complete forecast in accordance with project requirements.

(1) Model development

(2) Model calibration

(3) Model operation

59. Alternate streamflow forecasting procedures should be developed to meet the long-range hydrologic needs of the military. A single procedure or model cannot be used to forecast streamflows for the wide range of conditions expected to be encountered by the military hydrologist. In order to accomodate the time, data, facilities, and personnel constraints of the military, alternate procedures ranging from general guidelines and graphic procedures to advanced computer models will be required.

60. A long-term effort should be devoted towards the development of a worldwide hydrologic data base. The collection and processing of available hydrologic data for an area is time-consuming. Constraints may not allow the military hydrologist to gather and utilize these data unless it is in a readily available format. The data base should include

historical streamflows, regional statistical flood formulas, general watershed and channel characteristics, precipitation rates and patterns, and climatic information.

61. An effort should be devoted to relating stream discharge and stage frequency to basin and channel parameters for various regions of the world. Studies have shown that streamflow characteristics are related to channel and basin characteristics. This type of information combined with the worldwide data base would allow the hydrologist to make a reasonable drainage analysis of a battlefield area. It will provide him with the background necessary to make quick but reasonable estimates of channel cross sections, bank and stream bottom characteristics, stream discharge, depth, and velocities.

62. Long-term efforts should be directed towards developing a continuous streamflow simulation model compatible with military constraints and requirements. The optimum model for continuous forecasting of streamflows in ungaged watersheds for military application has not been developed. Most existing models require extensive historical information for calibration and were developed without consideration of military constraints.

63. The army that has the capability of predicting streamflows throughout the battlefield area some several hours in advance should have a tactical advantage on both the offense and the defense. Continuous simulation of all streams in the area would be desirable. Remotely operated stations at specific sites in the watershed could provide continuous, real-time information on precipitation, radiation, temperature, evaporation, soil moisture, and streamflows. These data would be telemetered to the computer and, when historical records are lacking, would be used initially to calibrate the hydrologic model to the watershed. After it has been calibrated, the model can be used to simulate streamflows throughout the battlefield area and predict streamflows based on the weather forecast.

64. In order to establish a continuous simulation model for a watershed, a large amount of data must be acquired and processed. The three major categories of input are (a) hydrometeorologic data,

(b) physical data, and (c) process parameters. The general concept of advanced data collection utilizing remote sensing procedures and telemetry, and automatic data processing using computers, is compatible with the distributed parameter hydrologic model. In this type of model, the watershed is divided into a large number of finite elements. Therefore, a distributed system of representing the watershed, compatible with future cross-country mobility models where the area is divided into a large number of triangular elements, should be developed. Algorithms utilized in the model should be representative of the hydrologic cycle. Parameters should be physically based and should be capable of being evaluated primarily from watershed and channel characteristics. A soil moisture model would be required to estimate the runoff and overland flow routing procedure used to develop the flow in the channel. Since the time interval for calculation will be small due to the size of the watershed elements, kinematic channel routing could be utilized.

65. Hydrometeorologic data drive the model and include precipitaton, evaporation, radiation, temperature, cloud cover, wind speed and direction, humidity, vapor pressure, stream velocity and discharge, and stream stage. Most of these data can be obtained by automatic recording and transmitting stations located in the watershed. These could be air-droppable stations. Ground radar and satellite imagery are also utilized to monitor and forecast precipitation. A major problem for military hydrology modeling efforts will be the lack of historical rainfall and streamflow data.

66. Physical data are required to define the retention and runoff characteristics of the watershed. Physical data have a high potential of being acquired by remote sensing procedures. Two general types of physical data are land surface data and drainage channel network data. Land surface data include area, elevation, slope, overland length and slope, vegetation, and soil type. If digital terrain data are available for the watershed, much of the work in adapting the model to the watershed can be automated and done with a computer. Channel network data can be obtained from maps, aerial photographs, and surveys and include

channel and floodplain cross-section dimensions, slope, roughness, and structures.

67. A deterministic simulation model uses mathematical relationships to describe the behavior of the hydrologic cycle. Process parameters such as infiltration, interflow, moisture storage, and groundwater flow reflect the watershed response. The parameters are used to adjust the mathematical expression in the model to the hydrologic processes. In the conceptual model, most of the process parameters are related to the physical process; reasonable estimates of these parameters can usually be determined from direct observations or past experience. The number of parameters to be evaluated during model calibration should be kept to a minimum as it is more difficult to arrive at the correct combination of the parameters that calibrate the model the more parameters there are. The hydrologic model will require several precipitation-runoff events for calibration.

68. It may require several months (or years) to obtain the data (primarily precipitation and streamflow) needed to calibrate the continuous simulation model. When battlefield constraints do not permit the development and calibration of this type of model, other alternatives should be available to the military hydrologist. A simple event simulation model could be established for the watershed and made operational in a time period of several days. Process parameters for the event simulation model would be estimated based on observations and past experience. It appears that the SCS curve number procedure for estimating runoff, the synthetic unit-hydrograph method of estimating the time distribution of runoff, and the hydrologic discharge/storage routing procedure for translating hydrographs downstream are the most suitable computational procedures for the event simulation model. If battlefield constraints do not permit the development of the event simulation model, the military hydrologist can develop rough streamflow forecasts based on general guidelines for the area in a time period of several hours.

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Table 1

Classification of Alluvial Channels*

Mode of Sediment Transport	Channel Sediment Silt-Clay, %	Proportion of Total Sediment Load		Channel Stability		
		Suspended Load, percent	Bedload percent	Stable (Graded Stream)	Depositing (Excess Load)	Eroding (Deficiency of Load)
Suspended load	30-100	85-100	0-15	Stable suspended-load channel. Width-depth ratio less than 7; sinuosity greater than 2.1; gradient relatively gentle.	Depositing suspended load channel. Major deposition on banks cause narrowing of channel; streambed deposition minor.	Eroding suspended-load channel. Streambed erosion predominant; channel widening minor.
Mixed load	8-30	65-85	15-35	Stable mixed-load channel. Width-depth ratio greater than 7 less than 24; sinuosity less than 2.1 and greater than 1.5; gradient moderate.	Depositing mixed-load channel. Initial major deposition on banks followed by streambed deposition.	Eroding mixed-load channel. Initial streambed erosion followed by channel widening.
Bedload	0-8	30-65	35-70	Stable bedload channel. Width-depth ratio greater than 25; sinuosity less than 1.5; gradient relatively steep.	Depositing bedload channel. Streambed deposition and island formation.	Eroding bedload channel. Little streambed erosion; channel widening predominant.

* From Schumm (1963).

Table 2

Rating of Event Simulation Procedures

Event Simulation Procedure	Minimum Historical Information	Parameter Evaluation by Remote Methods	Simple	Reliable	Adoptability to Area	Minimum User Judgment	Accuracy
Rainfall - Runoff							
SCS curve number	3	3	3	2	2	3	2
Soil-moisture accounting	1	1	1	3	1	2	3
Loss rate functions	2	1	2	2	1	2	2
Antecedent precipitation index	1	1	2	3	1	2	2
Time distribution of runoff							
Synthetic unit hydrograph	3	3	3	2	3	3	2
Derived unit hydrograph	1	1	3	3	1	3	3
Overland flow routing	3	3	1	2	1	1	3
Channel routing							
Hydrologic							
Discharge/storage/time	3	3	3	2	3	2	2
Inflow/outflow data	1	2	3	3	1	2	2
Hydraulic	3	3	1	3	2	1	3

Note: rating code: 1 = low, 2 = medium, 3 = high.

Table 3

Runoff Curve Numbers for Hydrologic Soil-Cover Complexes*

Land Use	Cover: Treatment or Practice	Cover: Hydrologic Condition	Hydrologic Soil Group**: A	B	C	D
Fallow	Straight row	--	77	86	91	94
Row crops	Straight row	Poor	72	81	88	91
		Good	67	78	85	89
	Contoured	Poor	70	79	84	88
		Good	65	75	82	86
	Contoured and terraced	Poor	66	74	80	82
		Good	62	71	78	81
Small grain	Straight row	Poor	65	76	84	88
		Good	63	75	83	87
	Contoured	Poor	63	74	82	85
		Good	61	73	81	84
	Contoured and terraced	Poor	61	72	79	82
		Good	59	70	78	81
Close-seeded legumes or rotation meadow	Straight row	Poor	66	77	85	89
		Good	58	72	81	85
	Contoured	Poor	64	75	83	85
		Good	55	69	78	83
	Contoured and terraced	Poor	63	73	80	83
		Good	51	67	76	80
Pasture or range		Poor	68	79	86	89
		Fair	49	69	79	84
		Good	39	61	74	80
	Contoured	Poor	47	68	81	88
		Fair	25	59	75	83
		Good	6	35	70	79
Meadow		Good	30	58	71	78
Woods		Poor	45	66	77	83
		Fair	36	60	73	79
		Good	25	55	70	77
Farmsteads		--	59	74	82	86
Roads (dirt)		--	72	82	87	89
(hard surface)		--	74	84	90	92

Note: From SCS National Engineering Handbook.

* Antecedent moisture condition II, and $A_I = 0.2\ A_p$ (see paragraphs 35-39).

** See paragraph 38 for definition of soil groups.

Table 4

Curve Numbers (CN) for Antecedent Moisture Conditions I and III*

CN for Condition II	CN for Conditions I	III	CN for Condition II	CN for Conditions I	III
100	100	100	60	40	78
99	97	100	59	39	77
98	94	94	58	38	76
97	91	99	57	37	75
96	89	99	56	36	75
95	87	98	55	35	74
94	85	98	54	34	73
93	83	98	53	33	72
92	81	97	52	32	71
91	80	97	51	31	70
90	78	96	50	31	70
89	76	96	49	30	69
88	75	95	48	29	68
87	73	95	47	28	67
86	72	94	46	27	66
85	70	94	45	26	65
84	68	93	44	25	64
83	67	93	43	25	63
82	66	92	42	24	62
81	65	92	41	23	61
80	63	91	40	22	60
79	62	91	39	21	59
78	60	90	38	21	58
77	59	89	37	20	57
76	58	89	36	19	56
75	57	88	35	18	55
74	55	88	34	18	54
73	54	87	33	17	53
72	53	86	32	16	52
71	52	86	31	16	51
70	51	85	30	15	50
69	50	84			
68	48	84	25	12	53
67	47	83	20	9	37
66	46	82	15	6	30
65	45	32	10	4	22
64	44	81	5	2	13
63	43	80	0	0	0
62	42	79			
61	41	78			

* From SCS National Engineering Handbook.

Table 5

Continuous Simulation Models

Model Name	Number of Parameters	Method of Calibration*	Watershed Size square miles
Hydrocomp Simulation Program	70	T & E	<40,000
Streamflow Synthesis and Reservoir Regulation	24	T & E	Large
Stanford Watershed - Model IV	34	Auto	All
Dawdy - O'Donnell	13	Auto	<1,000
Bouthton	14	Auto	< 275
Hyreun	5	Fixed	< 700
USDAHL** - 70	166	--	Small
Institute of Hydrology	9	Auto	< 500
UBC*** Watershed and Flow	9	T & E	<1,500

* T & E = trial and error; Auto = automatic optimization.
** U. S. Department of Agriculture Hydrograph Laboratory.
*** University of British Columbia.

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

James, Wesley P

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